CLEO-c and CESR-c: A New Frontier in Weak and Strong Interactions

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Abstract. We report on the physics potential of a proposed conversion of the CESR machine and the CLEO detector to a charm and QCD factory: "CLEO-c and CESR-c" that will make crucial contributions to flavor physics in this decade and offers our best hope for mastering non-perturbative QCD which is essential if we are to understand strongly coupled sectors in the new physics that lies beyond the Standard Model.

EXECUTIVE SUMMARY

A focused three year program of charm and QCD physics with the CLEO detector operating in the 3-5 GeV energy range at the Cornell Electron Storage Ring in Ithaca, NY, is proposed. The CLEO-c physics program includes a set of measurements that will substantially advance our understanding of important processes within the Standard Model of particle physics and set the stage for understanding the larger theory in which we imagine the Standard Model to be embedded. The program will be preceded by one year of bottomium running with CLEOIII in 2002.

The program revolves around the strong interaction and the pressing need to develop sufficiently powerful tools to deal with an intrinsically non-perturbative theory. At the present time, and for the last twenty years, progress in weak interaction physics and the study of heavy flavor physics has been achieved primarily by seeking the few probes of weak-scale physics that succesfully evade or minimise the role of strong interaction physics. The pre-eminence of the mode $B \to J/\psi K_S^o$ in measuring $sin2\beta$ arises from the absence of complications due to the strong interaction. Similarly, Heavy Quark Symmetry and the development of HQET enabled the identification of the zero-recoil limit as the best place to measure $b \to c\ell\nu$ exclusive decays as the strong intercation effects at this kinematic point are small and calculable. This method has become one of the two preferred ways to extract V_{cb}. If we had similar strategies that would allow us to extract V_{ub} from $b \to u\ell\nu$ without form factor uncertainties, and V_{td} and V_{ts} from B_d and B_s mixing respectively, without decay constant and bag parameter uncertainties, we would be well on the way to understanding the CKM matrix at the few per cent level.

The goal of flavor physics is to test the Standard Model description of CP violation by probing the unitarity of the CKM matrix. However this goal is in jeopardy. Across the spectrum of heavy quark physics the study of weak-scale phenomena and the extractiion of quark mixing paramters remain fundamentally limited by our restricted capacity to

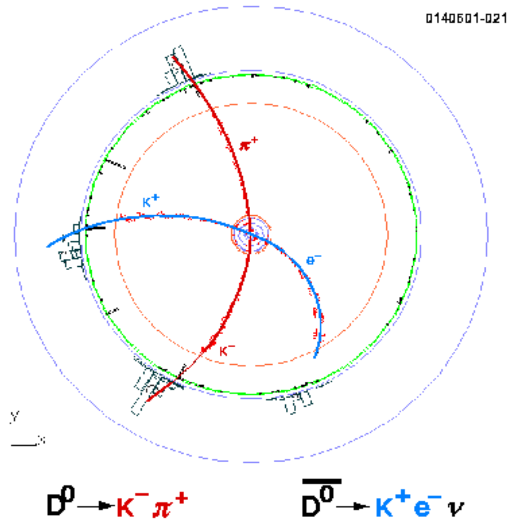

FIGURE 1. A doubly tagged event at the $\psi(3770)$

deal with the non-perturbative strong interaction dynamics.

Moreover, as we look to the future beyond the Standard Model, we anticipate that the larger theory in which the Standard Model is embedded will likely be strongly coupled, or have strongly coupled sectors. Both Technicolor, which is modeled on QCD and is ab initio strongly coupled, and Supersymmetry, which employs strongly coupled sectors to break the supersymmetry, are prime examples of candidates for physics beyond the Standard Model. Strong coupling is a phenomenon to be expected, weak coupling is the exception in field theory not the norm. However our ability to compute reliably in a strongly coupled theory is not well developed. Techniques such as lattice gauge theory that deal squarely with strongly coupled theories will eventually determine our progress on all fronts in particle physics. At the present time the absence of adequate theoretical tools significantly limits the physics we can obtain from the study heavy quarks.

Recent advances in Lattce QCD (LQCD) may offer hope. Algorithmic advances and improved computer hardware have produced a wide variety of non-perturbative results with accuracies at the 10-20% level for systems involving one or two heavy quark such as B and D mesons, and Ψ and Υ quarkonia. First generation unquenched calculations have been completed for decay constants and semileptonic form factors, for mixing and spectra. There is very strong interest in the LQCD community in pursuing much higher precision and the techniques needed to reduce uncertainties to 1-2% precision. But the push towards higher precision is hampered by the absence of accurate charm data against which to test and calibrate the new theoretical techniques.

CLEO-c will address this challenge in the charm system at threshold where the experimental conditions are optimal. We will obtain data samples several hundred times larger than any previous experiment and with a detector which is an order of magnitude better than any previous detector to operate at charm threshold. We will supplement the charm and charmonium data with bottomium data taken starting Fall 2001 with CLEO III prior to the conversion to CLEO-c. Decay constants, form factors, spectroscopy of

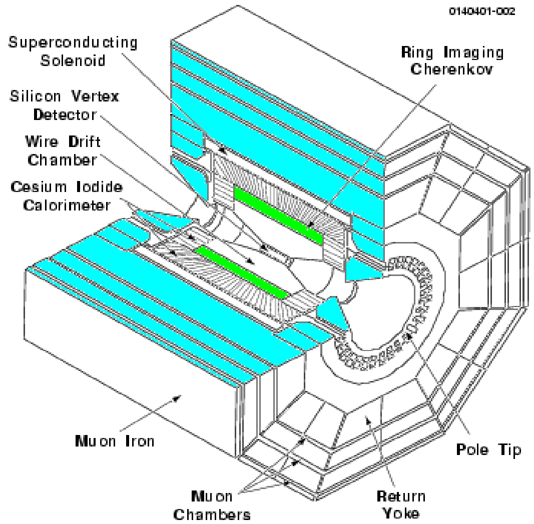

FIGURE 2. The CLEO III detector.

open and hidden charm and hidden bottom, and an immense variety of absolute branching ratio measurements will be obtained with accuracies at the 1-2% level. Precision measurements will demand precision theory.

The measurements described here are an essential and integral part of the global program in heavy flavor physics of this decade, and the larger program of the as yet unknown physics of the next decade.

INTRODUCTION

For many years, the CLEO experiment at the Cornell Electron Storage Ring, CESR, operating on the $\Upsilon(4S)$ resonance, has provided most of the world's information about the B_d and B_u mesons. At the same time, CLEO, using the copious continuum pair production at the $\Upsilon(4S)$ resonance has been a leader in the study of charm and τ physics. Now that the asymmetric B factories have achieved high luminosity, CLEO is uniquely positioned to advance the knowledge of heavy flavor physics by carrying out several measurements near charm threshold, at center of mass energies in the 3.5-5.0 GeV region. These measurements address crucial topics which benefit from the high luminosity and experimental constraints which exist near threshold but have not been carried out at existing charm factories because the luminosity has been too low, or have been carried out previously with meager statistics. They include:

1. Charm Decay constants f_D, f_{D_s}
2. Charm Absolute Branching Fractions
3. Semileptonic decay form factors
4. Direct determination of V_{cd} & V_{cs}

TABLE 1. Summary of CLEO-c charm decay measurements.

Topic	Reaction	Energy (MeV)	L (fb^{-1})	current sensitivity	CLEO-c sensitivity
Decay constant					
f_D	$D^+ \to \mu^+ \nu$	3770	3	UL	2.3%
f_{D_s}	$D_s^+ \to \mu^+ \nu$	4140	3	14%	1.9%
f_{D_s}	$D_s^+ \to \mu^+ \nu$	4140	3	33%	1.6%
Absolute Branching Fractions					
$Br(D^0 \to K\pi)$		3770	3	2.4%	0.6%
$Br(D^+ \to K\pi\pi)$		3770	3	7.2%	0.7%
$Br(D_s^+ \to \phi\pi)$		4140	3	25%	1.9%
$Br(\Lambda_c \to pK\pi)$		4600	1	26%	4%

5. QCD studies including:
   Charmonium and bottomonium spectroscopy
   Glueball and exotic searches
   Measurement of R between 3 and 5 GeV, via scans
   Measurement of R between 1 and 3 GeV, via ISR
6. Search for new physics via charm mixing, CP violation and rare decays
7. τ decay physics

The CLEO detector can carry out this program with only minimal modifications. The CLEO-c project is described at length in[1] -[11]. A very modest upgrade to the storage ring is required to achieve the required luminosity. Below, we summarize the advantages of running at charm threshold, the minor modifications required to optimize the detector, examples of key analyses, a description of the proposed run plan, and a summary of the physics impact of the program.

Advantages of running at charm threshold

The B factories, running at the Υ(4S) will have produced 500 million charm pairs by 2005. However, there are significant advantages of running at charm threshold:

1. Charm events produced at threshold are extremely clean;
2. Double tag events, which are key to making absolute branching fraction measurements, are pristine;
3. Signal/Background is optimum at threshold;
4. Neutrino reconstruction is clean;
5. Quantum coherence aids D mixing and CP violation studies

These advantages are dramatically illustrated in Figure 1, which shows a picture of a simulated and fully reconstructed $\psi(3770) \to D\bar{D}$ event.

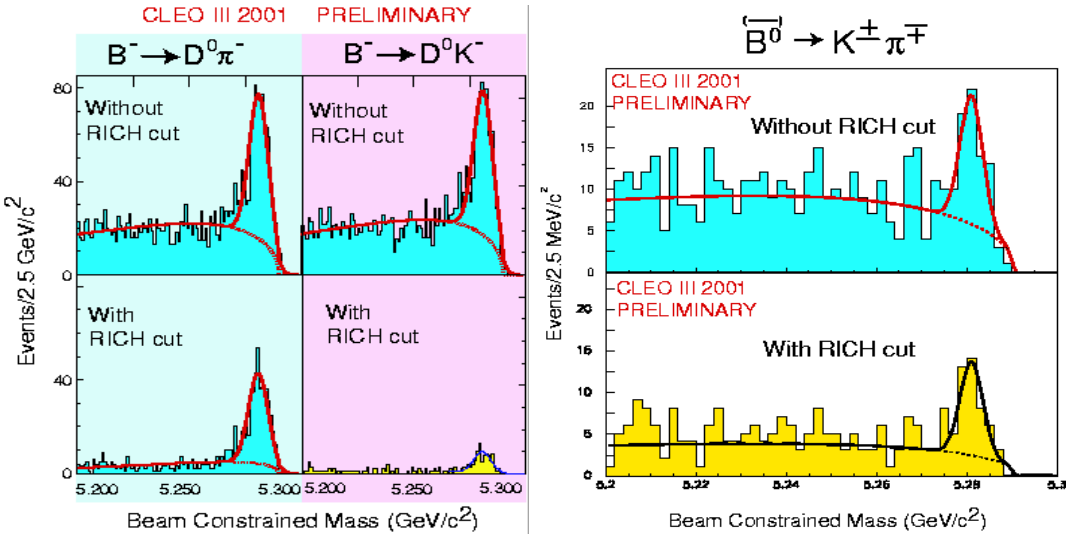

FIGURE 3. (Left) Beam constrained mass for the Cabibbo allowed decay $B \to D\pi$ and the Cabibbo suppressed decay $B \to DK$ with and without RICH information. The latter decay was extremely difficult to observe in CLEO II/II.V which did not have a RICH detector. (Right) The penguin dominated decay $B \to K\pi$. Both of these modes are observed in CLEO III with branching ratios consistent with those found in CLEO II/II.V.

The CLEO-III Detector : Performance, Modifications and issues

The CLEO III detector, shown in Figure 2, consists of a new silicon tracker, a new drift chamber, and a Ring Imaging Cherenkov Counter (RICH), together with the CLEO II/II.V magnet, electromagnetic calorimeter and muon chambers. The upgraded detector was installed and commissioned during the Fall of 1999 and Spring of 2000. Subsequently operation has been very reliable (see below for a caveat) and a very high quality data set has been obtained. To give an idea of the power of the CLEO III detector in Figure 3 (left plot) the beam constrained mass for the Cabibbo allowed decay $B \to D\pi$ and the Cabibbo suppressed decay $B \to DK$ with and without RICH information is shown. The latter decay was extremely difficult to observe in CLEO II/II.V which did not have a RICH detector. In the right plot of Figure 3 the penguin dominated decay $B \to K\pi$ and the tree dominated decay is shown. Both of these modes are observed in CLEO III with branching ratios consistent with those found in CLEO II/II.V. and are also in agreement with recent Belle and BABAR results. Figure 3 is a demonstration that CLEO III performs very well indeed.

Unfortunately, there is one detector subsystem that is not performing well. The CLEO III silicon has experienced an unexpected and unexplained loss of efficiency The situation is under constant evaluation. It is likely that the silicon detector will be replaced with a wire vertex chamber for CLEO-c. We note that if one was to design a charm factory detector from scratch the tracking would be entirely gas based to ensure that the detector material was kept to a minimum. CLEO-c simulations indicate that a simple six layer stereo tracker inserted into the CLEO III drift chamber as a silicon replacement would provide a system with superior momentum resolution to the current CLEO III

tracking system. We propose to build such a device for CLEO-c.

Due to machine issues we plan to lower the solenoid field strength to 1 T from 1.5 T. All other parts of the detector do not require modification. The dE/dx and Ring Imaging Cerenkov counters are expected to work well over the CLEO-c momentum range. The electromagnetic calorimeter works well and has fewer photons to deal with at 3-5 GeV than at 10 GeV. Triggers will work as before. Minor upgrades may be required of the Data Acquisition system to handle peak data transfer rates. CESR conversion to CESR-c requires 18 m of wiggler magnets, to increase transverse cooling, at a cost of $\sim$ $4M. The conclusion is that, with the addition of the replacement wire chamber, CLEO is expected to work well in the 3-5 GeV energy range at the expected rates.

Examples of analyses with CLEO-c

The main targets for the CKM physics program at CLEO-c are absolute branching ratio measurements of hadronic, leptonic and semileptonic decays. The first of these provides an absolute scale for all charm and hence all beauty decays. The second measures decay constants and the third measures form factors and in combination with theory allows the determination of V_{cd} and V_{cs}.

Absolute branching ratios

The key idea is to reconstruct a D meson in any hadronic mode. This, then, constitutes the tag. Figure 4 shows tags in the mode $D \to K\pi$. Note the y axis is a log scale. Tag modes are very clean. The signal to background ratio is $\sim$ 5000/1 for the example shown. Since $\psi(3770) \to D\bar{D}$, reconstruction of a second D meson in a tagged event to a final state X, corrected by the efficiency which is very well known, and divided by the number of D tags, also very well known, is a measure of the absolute branching ratio $Br(D \to X)$. Figure 5 shows the $K^-\pi^+\pi^+$ signal from doubly tagged events. It is essentially background free. The simplicity of $\psi(3770) \to D\bar{D}$ events combined with the absence of background allows the determination of absolute branching ratios with extremely small systematic errors. This is a key advantage of running at threshold.

Leptonic decay $D_s \to \mu\nu$

This is a crucial measurement because it provides information which can be used to extract the weak decay constant, f_{D_s}. The constraints provided by running at threshold are critical to extracting the signal.

The analysis procedure is as follows:

1. Fully reconstruct one D;
2. Require one additional charged track and no additional photons;

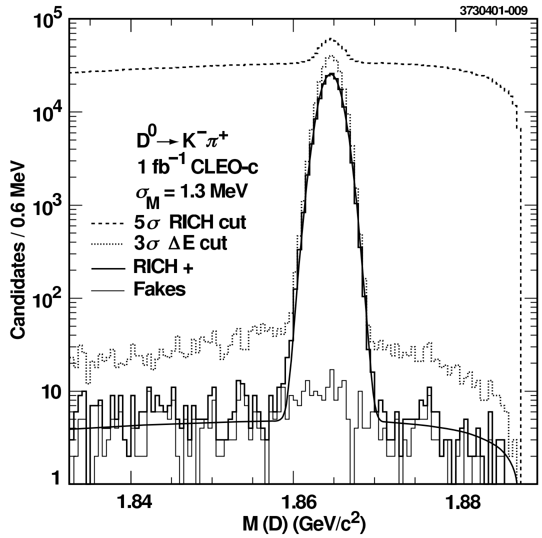

FIGURE 4. $K\pi$ invariant mass in $\psi(3770) \to D\overline{D}$ events showing a strikingly clean signal for $D \to K\pi$. The y axis is logarithmic. The S/N $\sim$ 5000/1.

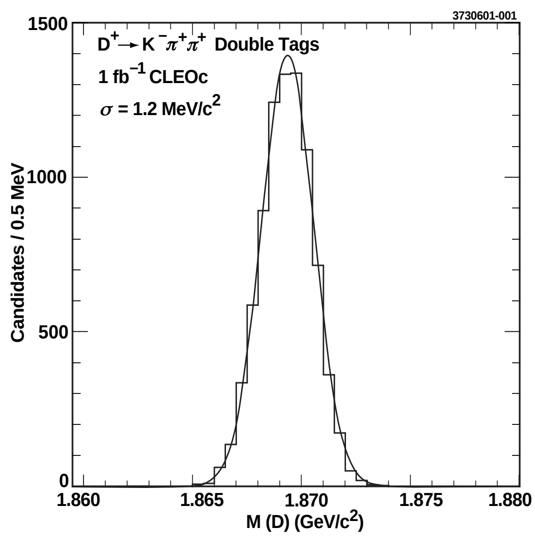

FIGURE 5. $K\pi\pi$ invariant mass in $\psi(3770) \to D\overline{D}$ events where the other D in the event has already been reconstructed. A clean signal for $D \to K\pi\pi$ is observed and the absolute branching ratio $Br(D \to K\pi\pi)$ is measured by counting events in the peak.

3. Compute the missing mass squared (MM2) which peaks at zero for a decay where only a neutrino is unobserved.

The missing mass resolution, which is of order $\sim M_{\pi^0}$, is sufficient to reject the backgrounds to this process as shown in Fig. 6. There is no need to identify muons, which helps reduce the systematic error. One can inspect the single prong to make sure it is not an electron. This provides a check of the background level since the leptonic decay to an electron is severely helicity-suppressed and no signal is expected in this

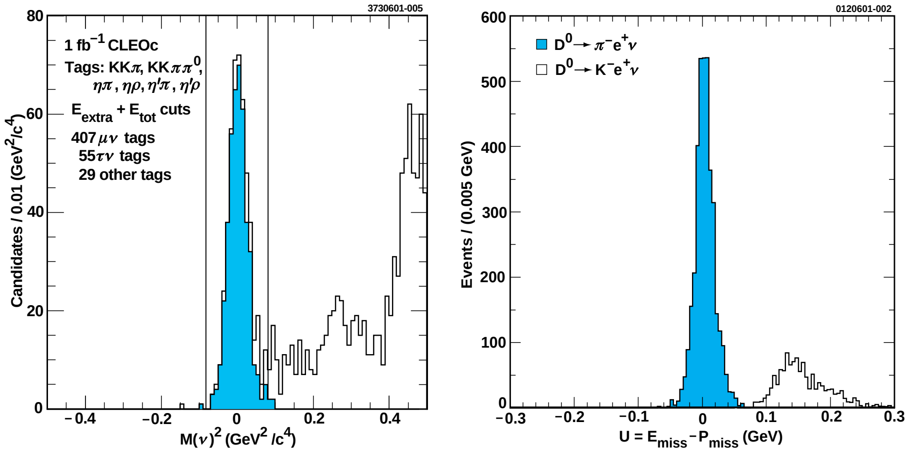

FIGURE 6. (Left) Missing mass for D_sD_s tagged pairs produced at $\sqrt{s} = 4100$ MeV. Events due to the decay $D_s \to \mu\nu$ are shaded. (Right) The difference between the missing energy and missing momentum in $\psi(3770)$ tagged events for the Cabibbo suppressed decay $D \to \pi\ell\nu$ (shaded). The unshaded histogram arises from the ten times more copiously produced Cabibbo allowed transition $D \to K\ell\nu$ where the K is outside the fiducial volume of the RICH.

mode.

Semileptonic decay $D \to \pi\ell\nu$

The analysis procedure is as follows:

1. Fully reconstruct one D
2. Identify one electron and one hadronic track.
3. Calculate the variable, $U = E_{miss} - P_{miss}$, which peaks at zero for semileptonic decays.

Using the above procedure results in the right plot of Figure 6. With CLEO-c for the first time it will become possible to make absolute branching ratio and absolute form factor measurements of every charm meson semileptonic pseudoscalar to pseudoscalar and pseudoscalar to vector transition. This will be a lattice calibration data set without equal. Figure 7 graphically shows the improvement in absolute semileptonic branching ratios that CLEO-c will make.

Run Plan

CLEO-c must run at various center of mass energies to achieve its physics goals. The “run plan” currently used to calculate the physics reach is given below. Note that item 1 is prior to machine conversion and the remaining items are post machine conversion.

1. 2002 : Υ’s – 1-2 fb^{-1} each at $\Upsilon(1S), \Upsilon(2S), \Upsilon(3S)$

$1: D^0 \to K^- e^+ \nu$
$2: D^0 \to K^{*-} e^+ \nu$
$3: D^0 \to \pi^- e^+ \nu$
$4: D^0 \to \rho^- e^+ \nu$
$5: D^+ \to \bar{K}^0 e^+ \nu$
$6: D^+ \to \bar{K}^{*0} e^+ \nu$
$7: D^+ \to \pi^0 e^+ \nu$
$8: D^+ \to \rho^0 e^+ \nu$
$9: D_s \to K^0 e^+ \nu$
$10: D_s \to K^{*0} e^+ \nu$
$11: D_s \to \phi e^+ \nu$
$12: \Lambda_c \to \Lambda e^+ \nu$

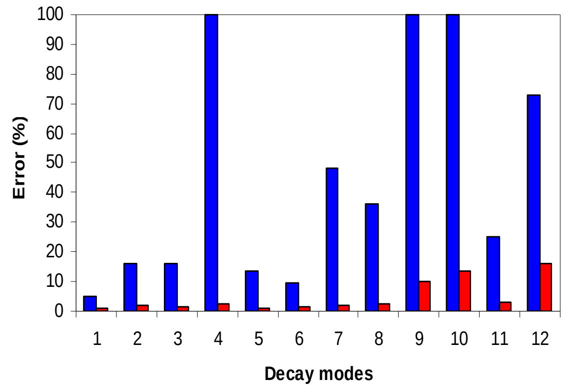

FIGURE 7. Absolute branching ratio current precision from the PDG (left entry) and precision attainable at CLEO-c (right entry) for twelve semileptonic charm decays.

Spectroscopy, electromagnetic transition matrix elements, the leptonic width. Γ_{ee}, and searches for the yet to be discovered h_b, η_b with 10-20 times the existing world's data sample.

2. 2003 : $\psi(3770) - 3\ fb^{-1}$
   30 million events, 6 million tagged D decays (310 times MARK III)
3. 2004 : 4100 MeV – 3 fb^{-1}
   1.5 million D_sD_s events, 0.3 million tagged D_s decays (480 times MARK III, 130 times BES)
4. 2005 : $J/\psi - 1\ fb^{-1}$
   1 Billion J/ψ decays (170 times MARK III, 20 times BES II)

Physics Reach of CLEO-c

Tables 1, 2 , and 3, and Figures 7 and 8 summarize the CLEO-c measurements of charm weak decays, and compare the precision obtainable with CLEO-c to the expected precision at BABAR which expects to have recorded 500 million charm pairs by 2005. CLEO-c clearly achieves far greater precision for many measurements. The reason for this is the ability to measure absolute branching ratios by tagging and the absence of background at threshold. In those analyses where CLEO-c is not dominant it remains comparable or complementary to the B factories.

Also shown in Table 3 is a summary of the data set size for CLEO-c and BES II at the J/ψ and ψ', and the precision with which R, the ratio of the e^+e^- annihilation cross section into hadrons to mu pairs, can be measured. The CLEO-c data sets are over an order of magnitude larger, the precision with which R is measured is a factor of three higher, in addition the CLEO detector is vastly superior to the BES II detector. Taken together the CLEO-c datasets at the J/ψ and ψ' will be qualitatively and quantitatively superior to any previous dataset in the charmonium sector thereby providing discovery potential for glueballs and exotics without equal.

TABLE 2. Summary of direct CKM reach with CLEO-c

Topic	Reaction	Energy (MeV)	L (fb^{-1})	current sensitivity	CLEO-c sensitivity
V_{cs}	$D^0 \to K\ell^+\nu$	3770	3	16%	1.6%
V_{cd}	$D^0 \to \pi\ell^+\nu$	3770	3	7%	1.7%

TABLE 3. Comparision of CLEO-c reach to BaBar and BES

Quantity	CLEO-c	BaBar	Quantity	CLEO-c	BES-II
f_D	2.3%	10-20%	$\#J/\psi$	10^9	5×10^7
f_{D_s}	1.7%	5-10%	ψ'	10^8	3.9×10^6
$Br(D^0 \to K\pi)$	0.7%	2-3%	4.14 GeV	$1 fb^{-1}$	$23 pb^{-1}$
$Br(D^+ \to K\pi\pi)$	1.9%	3-5%	3-5 R Scan	2%	6.6%
$Br(D_s^+ \to \phi\pi)$	1.3%	5-10%			

CLEO-c Physics Impact

CLEO-c will provide crucial validation of Lattice QCD, which will be able to calculate with accuracies of 1-2%. The CLEO-c decay constant and semileptonic data will provide a "golden", and timely test while CLEO-c QCD and charmonium data provide additional benchmarks.

CLEO-c will provide dramatically improved knowledge of absolute charm branching fractions which are now contributing significant errors to measurements involving b's in a timely fashion. CLEO-c will significantly improve knowledge of CKM matrix elements which are now not very well known. V_{cd} and V_{cs} will be determined directly by CLEO-c data and LQCD, or other theoretical techniques. V_{cb}, V_{ub}, V_{td} and V_{ts} will be

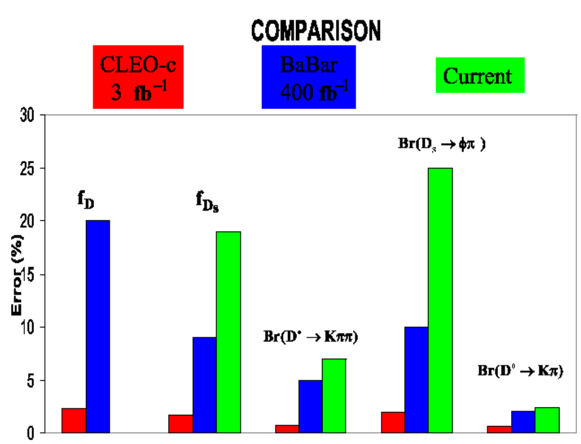

FIGURE 8. Comparison of CLEO-c (left) BaBar (center) and PDG2001 (right) for five physics quantities indiocated in the key.

TABLE 4. Current knowledge of CKM matrix elements (row one). Knowledge of CKM matrix elements after CLEO-c (row two). See the text for further details.

V_{cd}	V_{cs}	V_{cb}	V_{ub}	V_{td}	V_{ts}
7%	16%	5%	25%	36%	39%
1.7%	1.6%	3%	5%	5%	5%

determined with enormously improved precision using B factory data once the CLEO-c program of lattice validation is complete. Table 4 give a summary of the situation.

CLEO-c data alone will also allow new tests of the unitarity of the CKM matrix. The unitarity of the second row of the CKM matrix will be probed at the 3% level which is comparable to our current knowledge of the first row. CLEO-c data will also test unitarity by measuring the ratio of the long sides of the squashed *cu* triangle to 1.3%.

Finally the potential to observe new forms of matter; glueballs, hybrids, etc in J/ψ decays and new physics through sensitivity to charm mixing, CP violation, and rare decays provides a discovery component to the program.

ACKNOWLEDGMENTS

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